NOTICE

This material has been funded wholly or in part by Interagency Agreements among the U.S. Environmental Protection Agency (EPA), the National Aeronautics and Space Administration (NASA), and the U.S. Air Force (USAF). These agreements concern "Technical Assessment of Alternative Technologies for Aerospace Depainting Operations."

EXECUTIVE SUMMARY

The National Aeronautics and Space Administration (NASA) is conducting a technical assessment of alternative technologies for aerospace depainting operations on behalf of the Environmental Protection Agency (EPA) and the United States Air Force (USAF). Such technologies are to be used as paint stripping processes that do not adversely affect the environment and that specifically do not involve the use of methylene chloride.

During this reporting period, NASA was involved in the following activities:

- NASA personnel visited General Lasertronics Corporation to observe a carbon dioxide (CO_2) laser stripping system and welcomes General Lasertronics Corporation as a new committee member to assist with process evaluation.

- Personnel from the Environmental Protection Agency visited Marshall Space Flight Center (MSFC) for an in-depth program review of the interagency study.

- Control panels were painted, aged, and distributed for the third depainting sequence.

- During Sequence 3, four depainting processes (chemical stripping, FLASHJET®, plastic media blasting, and ENVIROSTRIP® wheat starch) were used on control panels. Sequence 3 data for the CO_2 laser, sodium bicarbonate wet stripping, and WaterJet processes will be available after the publication date of this report and will be presented in the final report.

- Interim measurements were made on the control panels for surface roughness, weight and thickness, and coating thickness. No significant changes in surface roughness measurements were seen after Sequences 2 and 3. Post-stripping surface roughnesses decreased slightly, probably a result of the presence of less remnant primer from the mechanical processes as operator skills improved.

- The control panels for chemical stripping, plastic media blasting, FLASHJET®, and ENVIROSTRIP® wheat starch were reprocessed, which included cleaning, chromate conversion coating, priming, and painting.

- A method of loading thin specimens into the fatigue tester was developed to allow fatigue testing of specimens without twisting. Baseline data collection resumed for fatigue life comparisons.

- Further analysis was performed on sandwich corrosion specimens to evaluate the extreme effect of deionized water.

- Hydrogen embrittlement effects of the environmentally advantaged chemical strippers on high-strength steel were determined.

- This progress report was published in July 1998.

ACKNOWLEDGMENTS

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- The U.S. Environmental Protection Agency (especially the Emission Standards Division)
- The National Aeronautics and Space Administration, including the NASA Operational Environment Team, the MSFC Systems Analysis and Integration Laboratory, the MSFC Materials and Processes Laboratory, and MSFC contractor personnel from Native American Services, Inc., and IIT Research Institute
- The USAF's Materiel Command and Corrosion Control Laboratory, as well as Cape Canaveral Air Station, Davis Monthan Air Force Base (AFB) (including Aerospace Maintenance and Regeneration Center), Robins AFB (including Warner Robins Air Logistics Center), and Tinker AFB
- The U.S. Army Depot at Corpus Christi
- The U.S. Coast Guard

as well as to our Technical Advisory Committee and other members of private industry, including:

Aircraft Owners & Pilots Association	General Lasertronics Corporation
The Boeing Company	Lockheed-Martin Space Operations
CAE Electronics, Ltd.	Martin Marietta
Carolina Equipment	McDonnell Douglas Aerospace (Boeing-St. Louis)
Delta Airlines	Northrop Grumman
Duncan Aviation	Raytheon Aerospace
Garrett Aviation	Sikorsky Aircraft Corporation
Grumman Aerospace	United Airlines
Hamilton Standard	United Space Boosters, Inc.

We appreciate the active cooperation of several companies whose products are under evaluation:

3M Corporation	INTA
ADM/Ogilvie	International Specialty Products
Amax Industrial Products Group	ManGill Chemical Company
ARCO Chemical Company	Maxwell Laboratory
Autre Products, Ltd.	McDonnell Douglas Aerospace (Boeing-St. Louis)
BIX Processing Systems	McGean-Rohco, Inc.
Brulin Corporation	National Solvent Corporation
CAE Electronics, Ltd.	Orchem, Inc.
Calgon Corporation	Pratt & Whitney
Carolina Equipment	PyRock Chemical
ColdJet	Savogran Company
Diversey Corporation	Silicon Alps
Dynacraft Industries	S&S Carbonic Industries
Ecolink, Inc.	Titan Abrasive Systems
Eldorado Chemical Company	TOMCO$_2$ Equipment Company
Fine Organics Corporation	Turco Products, Inc.
Gage Products Company	

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Acronyms and Abbreviations

AMS	Aerospace Materials Specification
A	Ampere
CO_2	Carbon dioxide
cm	Centimeter
EDM	Electro-Discharge Machine
ESC	Electron Spectroscopy for Chemical Analysis
deg	Degree
ft	Foot
g	Gram
gal	Gallon
gpm	Gallons per minute
hr	Hour
HR_C	Rockwell hardness C
Hz	Hertz
IA	Interagency Agreement
IACS	International Annealed Copper Standard
in.	Inch
J	Joule
kg	Kilogram
ksi	Thousand pounds per square inch
ksi√in.	Thousand pounds per square inch times square root inch (fracture toughness unit)
kW	Kilowatt
L	Liter
lb	Pound
LN_2	Liquid nitrogen
mg	Milligram
mil	One-thousandth of an inch
MIL-	Military specification
min	Minute
mL	Milliliter
mm	Millimeter
MPa	Million Pascals
n/a	Not applicable
NESHAP	National Emission Standard for Hazardous Air Pollutants
oz	Ounce
PEL	Permissible Exposure Level
pH	Hydrogen-ion concentration
PMB	Plastic Media Blasting
ppm	Parts per million
psi	Pounds per square inch
sec	Second
-T#	Temper number
V	Volt
x	Times (magnification level)

Organizations

ADM	Archer Daniels Midland Company
AFB	Air Force Base
AISI	American Iron and Steel Institute
ASTM	American Society for Testing & Materials
CAE	CAE Electronics, Ltd.
EH01	MSFC Materials and Processes Laboratory
EH12	MSFC Physical Science and Environmental Effects Branch
EH22	MSFC Metallurgical Engineering Branch
EH23	MSFC Metallurgy Research and Development Branch
EH33	MSFC Nonmetallic Processes Branch
EH42	MSFC Environmental and Analytical Chemistry Branch
EPA	Environmental Protection Agency
IATA	International Air Transport Association
ISO	International Standards Organization
ITT	Illinois Institute of Technology
MDA	McDonnell Douglas Aerospace (now Boeing-St. Louis)
MSFC	Marshall Space Flight Center
MTS	MTS Systems Corporation
NAS	Native American Services, Inc.
NASA	National Aeronautics and Space Administration
OSHA	Occupational Safety and Health Administration
SAE	Society of Automotive Engineers
TAC	Technical Advisory Committee
TIC	Technical Implementation Committee
USAF	United States Air Force

Symbols

~	Approximately
<	Less than
>	Greater than
≤	Less than or equal to
≥	Greater than or equal to
+	Plus
–	Minus
±	Plus or minus
÷	Divided by
#	Number
°	Degree
°C	Degree Celsius
°F	Degree Fahrenheit
µin.	Microinch
µsec	Microsecond
%	Percent
R	Minimum ÷ maximum load
R_a	Arithmetic mean roughness value
®	Registered trademark
™	Trademark

Elements

As	Arsenic
C	Carbon
Cd	Cadmium
H	Hydrogen
N	Nitrogen
Na	Sodium
O	Oxygen

1.0 INTRODUCTION

1.1. Background

The National Aeronautics and Space Administration is conducting a technical assessment of alternative technologies for aerospace depainting operations in a cooperative effort with the Environmental Protection Agency and the U.S. Air Force. This interagency study was designed to evaluate an array of depainting processes that do not use methylene chloride, a probable carcinogen that is the active ingredient in many popular and widely used paint stripping products. The nine techniques subdivide into five removal method categories (abrasive, impact, cryogenic, thermal, and molecular bonding disassociation). Seven techniques are currently being investigated as alternatives to the use of methylene chloride.

The use of methylene chloride has been restricted in depainting operations per the National Emission Standard for Hazardous Air Pollutants (NESHAP) for Aerospace Manufacturing and Rework Facilities. The effective date of Maximum Achievable Control Technology regulation was September 1995, with the first substantive compliance date for existing sources being September 1998.

Industrial concerns may also wish to consider substituting another paint stripping process for methylene chloride to avoid compliance costs associated with a new standard adopted by the Occupational Safety and Health Administration (OSHA), which sharply limits permissible exposure levels (PELs) for workers. Employers must ensure that no employee is exposed to an airborne concentration of methylene chloride as an 8-hour time-weighted PEL in excess of 25 ppm or a 15-minute short-term exposure level in excess of 125 ppm, whereas the previous PEL was 500 ppm. The final rule includes requirements for exposure monitoring, medical surveillance, and respiratory protection. It was adopted on January 10, 1997, and put into effect on April 10, 1997.

1.2. Scope of Study

These tests were designed to be conducted on one paint system (epoxy primer in accordance with MIL-P-23377F, Type 1, Class 2, with a polyurethane topcoat, originally MIL-C-83286B but now MIL-C-85285B) applied to two substrate materials (clad and non-clad 2024-T3 aluminum in four thicknesses), processed in accordance with draft 4 of the International Standards Organization/Society of Automotive Engineers (ISO/SAE) MA4872, "IATA Guidelines for Evaluation of Aircraft Paint Stripping Materials and Processes." (See excerpt in Appendix A.1.) The specimens were then to be depainted under controlled conditions.

The results presented here are representative of this particular test protocol. Changing the processing and depainting parameters may yield different results, even on the same substrate and paint system. This report should be used as a guidance document when selecting an alternative depainting method, as it does not recommend any one depainting method over another. End users should consider the maturity of their facilities, equipment, and personnel training when analyzing process applicability for their operations.

1.2.1. Materials Selection

This study uses materials, coatings, and processes found in ISO/SAE MA4872 (draft 4), including other standards referenced under Section 2.0, Applicable Documents, in that draft. To ensure manageable parameters and data comparable to those available on similar substrates, NASA, the EPA, and the concerned industrial partners known as the Technical Advisory Committee (TAC) agreed to limit this study to one coating system on two substrate materials, as discussed below.

As referenced in the rest of this report, "Sequence 3" is used to designate the third iteration of activity (including processing, artificial aging, and depainting of the control panels, followed by data evaluation) that was conducted for this study.

1.2.1.1. Coating System

Plans called for use of the baseline paint system referenced in ISO/SAE MA4872 (draft 4), which is comprised of a high-solvents polyurethane topcoat, gloss finish, white #17925 (in accordance with MIL-C-83286B) applied over an epoxy primer (in accordance with MIL-P-23377F, Type 1, Class 2). These coatings exceed limits established in the Aerospace NESHAP, but they were partnered as a preferred paint system for many years, building a strong database of performance information.

The MIL-C-83286B topcoat, however, became unavailable after the processing of panels for Sequence 1. It has been replaced with a high-solids aliphatic polyurethane coating (in accordance with MIL-C-85285B). The Aerospace NESHAP does not require any changes for the high-solids epoxy primer (in accordance with MIL-P-23377F, Section 1.2). This revised paint system was incorporated at the beginning of Sequence 2 and is being used throughout the remainder of the study. (See Table 1.2.1.1-1.)

Table 1.2.1.1-1. Substrate Coating System

Surface Treatment	Primer	Topcoat
Iridite 14-2	MIL-P-23377F, Type 1, Class 2 (0.6 to 0.9 mil)	MIL-C-85285B (1.7 to 2.3 mil)

1.2.1.2. Test Substrates

The substrate material is 2024-T3 aluminum (clad and non-clad) in four thicknesses: 0.016, 0.032, 0.051, and 0.064 inches. Substrate requirements are detailed in SAE Aerospace Materials Specification (AMS) 4041, “Sheet and Plate,” and AMS 4037, "Aluminum Alloy Sheet and Plate." (See Table 1.2.1.2-1.)

Table 1.2.1.2-1. Control Panels (Initial Material)

Material	Specification	Thickness	Quantity
Clad 2024-T3 aluminum	AMS 4041 or Federal QQ-A-250/5	0.016 in.	3
		0.032 in.	3
		0.064 in.	16
Non-clad 2024-T3 aluminum	AMS 4037 or Federal QQ-A-250/4	0.016 in.	21
		0.051 in.	16
		0.064 in.	16

In addition, Sikorsky Aircraft Corporation provided 80 panels of clad 2024-T3 aluminum in two thicknesses. (See Table 1.2.1.2-2.) The processes using these clad panels are the in-house processes: plastic media blasting (PMB), WaterJet blasting, and sodium bicarbonate wet stripping. Data from PMB clad panels appear in this report. The chemical stripping process had included 0.064-inch thick clad panels for evaluation from the beginning, and because panel thickness is irrelevant for chemical stripping, no Sikorsky panels were added to this process.

Table 1.2.1.2-2. Control Panels (Additional Clad Material)

Material	Specification	Dimensions	Thickness	Quantity
Clad 2024-T3 aluminum	Federal QQ-A-250/5	22 in. wide by 22 in. long	0.016 in.	40
			0.032 in.	40

1.2.2. Sample Preparation

Initially, the specimens were cut to appropriate sizes and uniquely numbered, so that they could be tracked throughout the study. Then, several preparation steps were used to develop the baseline data. (See Table 1.2.2-1.)

Table 1.2.2-1. Initial Sample Preparation

Step	Action
1	Hand-wipe specimens with methyl ethyl ketone.
2	Clean specimens, *i.e.*, degrease, alkaline clean, rinse with deionized water, deoxidize, final rinse with deionized water.
3	Apply chromate conversion coating (Iridite 14-2).
4	Measure baseline substrate thickness.
5	Measure baseline surface roughness and weights.

Standard ISO/SAE MA4872 (draft 4) requires five depainting sequences, each of which begins with the application of primer. From this point, a sequence includes the process details listed in Table 1.2.2-2.

Table 1.2.2-2. Sequence Activities

Step	Action
1	Apply primer.
2	Apply topcoat and cure at 122 ±5 °F for 24 hr.
3	Verify coating thickness.
4	Age specimens.
5	Distribute specimens to be stripped by methods under review.
6	Hand-wipe specimens with methyl ethyl ketone.
7	Clean specimens, *i.e.*, degrease, alkaline clean, rinse with deionized water, deoxidize, final rinse with deionized water.
8	Apply chromate conversion coating (Iridite 14-2).
9	Measure substrate thickness.
10	Measure surface roughness and weights.

Each step is in accordance with the procedures outlined in ISO/SAE MA4872 (draft 4).

1.2.3. Artificial Aging

NASA, the EPA, and the TAC selected an aging sequence in compliance with the version of ISO/SAE MA4872 available at that time, *i.e.*, draft 4, which has been superseded by four drafts. The TAC industry partners strongly suggested that this study closely follow the parameters provided in Appendix C of that document, which describes an intense aging scenario. (See Table 1.2.3-1.)

Table 1.2.3-1. Aging Procedure for Test Substrates per ISO/SAE MA4872 (Draft 4)

Step	Action
1	Precondition for 12 hr at 120 °F and 95% relative humidity.
2	Hold at -65 °F for 1 hr.
3	Thermally cycle aging chamber 400 times, each time cycling from -65 to 160 to -65 °F within 30 min.
4	Return aging chamber to ambient temperature.
5	Repeat steps 1 through 4.

Specimens are being aged in two thermal humidity chambers at MSFC. NASA was unable to meet the temperature ramp in 30 to 50 minutes (step 3) with a full aging chamber; therefore, the EPA and the TAC agreed to age specimens at the fastest rate that would allow them to be exposed to the temperature extremes defined in the aging profile. All participants indicated that they understood that the overall study timeline would be greatly impacted by this aging procedure, which proved quite lengthy. Ramifications included:

- During initial aging sessions, each temperature cycle required 3 hours to complete (rather than the specified 30 minutes), which resulted in a 97-day aging sequence.
- In May 1996, liquid nitrogen (LN_2) cooling lines were run to two thermal humidity chambers used for aging. This modification increased cooling rates by ~60% and reduced temperature ramp times by ~40%. Each temperature ramp now requires 1.5 hours to complete, which has resulted in a 51-day aging sequence.

1.2.4. Process Evaluation

When considering the results discussed in this report, the reader should bear in mind that many restrictions were required to maintain a manageable scope for our study.

Evaluation of the alternative methods will be determined through (1) analysis of results from measurements made on substrate thickness and weight, surface roughness, and surface chemical analysis throughout the sequences of preparation and stripping, (2) comparison of strip rates among the observed methods, and (3) further metallurgical evaluations of the substrate after final sequences of specimen preparation and stripping.

1.2.5. Schedule

The original scope of work and statement of tasks call for extensive and detailed data capture during each step of specimen preparation and stripping for all five depainting sequences. The revised project scope entails five full depainting sequences for the chemical stripping process, four full cycles for PMB, and three full cycles for the FLASHJET®, CO_2 laser, sodium bicarbonate wet stripping, WaterJet, and ENVIROSTRIP® wheat starch procedures. The projected schedule takes the depainting evaluation activities through the 1998 calendar year. (See Table 1.2.5-1.) The final report will contain all remaining data, as well as metallurgical evaluations of the processes. This report will be published in January 1999.

Table 1.2.5-1. Depainting Study Schedule

Action	Date
EPA/NASA Interagency Agreement (IA) signed	12/93
Executive Steering Task Force formed	2/94
Technical Implementation Committee (TIC) formed	2/94
First progress report published	8/94
USAF/NASA IA signed	9/94
Second progress report published	4/95
Test specimens acquired and machined	3/95 to 8/95
Third progress report published	10/95
EPA/NASA IA Amendment I signed	11/95
Depainting Sequence 1	8/95 to 5/96
Fourth progress report published	11/96
EPA/NASA IA Amendment II signed	9/96
Depainting Sequence 2	6/96 to 5/97
Fifth progress report published	11/97
Depainting Sequence 3	1/97 to 7/98
Sixth progress report published	7/98
Remainder of stripping sequences	6/97 to 10/98
Metallurgical specimens machining	5/98 to 9/98
Metallurgical evaluation	6/98 to 11/98
Data compilation and analysis	8/98 to 12/98
Final report published	1/99

2.0 SITE VISITS

2.1. Hydrogen Peroxide Exposure Tests

The Hydrogen Peroxide Exposure Testing study is designed to determine whether certain concentrations of hydrogen peroxide actually cause corrosion or brightening of the aluminum surface as described in this progress report. Results of the initial gross test for hydrogen peroxide corrosion on the specified aluminum surfaces were inconclusive because similar surfaces gave inconsistent surface roughness data. Also, the metallographic camera produced visual data based how the test specimens were cut. The test is being reconfigured to improve control over the cutting of the sample and to identify the surface side. The reconfigured test will enable collection of pretest surface roughness and metallographic camera data for posttest comparisons.

The MSFC point of contact is EH42/Jimmy Perkins at (256) 544-2634.

2.2. General Lasertronics Corporation

On June 12, 1997, Steve Burlingame made a trip to General Lasertronics Corporation, then located in Milpitas, California. The purpose of his trip was to set up an agreement whereby Lasertronics would assume the CO_2 laser stripping responsibilities previously held by INTA of Santa Clara, California. General Lasertronics Corporation was chosen as the most likely candidate for continuing the remaining CO_2 laser stripping cycles because the company is familiar with our requirements; is currently developing, manufacturing, and selling laser coating removal systems; has personnel experienced in engineering, manufacturing, and marketing with experience in aerospace, simulation, electronics, and optics; and has commitment to help this EPA/NASA/USAF Depainting Study meet its objectives.

Burlingame met with Phil Barone/President, Ralph Miller/Director, Marketing Communications, and Jim Thomas/Vice President, Engineering. He was given a detailed overview of both Lasertronics' coating removal capabilities and the experience of their personnel, and he toured the laser stripping facility and observed their stripping operations, which are similar to those that will be used to strip the aluminum test panels. The company accepted a letter of intent from Dr. Ann Whitaker/Director of the Materials and Processes Laboratory and will participate in this study by assisting in meeting the requirements of the study's technical objectives.

This study team thanks INTA for their participation and notes that the pursuit of another company to complete the CO_2 laser stripping cycles was driven by scheduling issues, not by technical concerns.

2.3. EPA Visit

In September 1997, Al Wehe and Barbara Driscoll, who, at the time, were EPA co-leads for the Interagency Agreement, visited Marshall Space Flight Center. During this “Depainting Project Review,” MSFC personnel provided the EPA visitors with a comprehensive status of the study. This status included a discussion of the overall scope of the study and the decision process in determining that scope, a review of the sequence of events in each iteration of stripping required of the panels, a current status of the panels tagged to each process, a review of the interim measurements required and their purpose, an overview of all metallurgical evaluations to be performed and a status of those activities, and detailed discussions of schedule, cost, and aging issues.

The EPA guests also toured the MSFC facilities. This tour included the cleaning facility, the paint shop, the aging chambers, and the equipment setup for in-house stripping activities, with demonstrations of certain stripping processes. (See Figures 2.3-1 through 2.3-5.)

Figure 2.3-1. Jeneene Sams, Robin Broad, Johnnie Clark, Barbara Driscoll, Al Wehe, and Beth Cook (l to r) observe one of the panel cleaning vats in the MSFC cleaning facility.

Figure 2.3-2. Wehe tries his hand at plastic media blasting.

Figure 2.3-3. Cook, Clark, Wehe, Driscoll, and Sams observe the fan nozzle used in the sodium bicarbonate depainting technique. David Hoppe holds the nozzle.

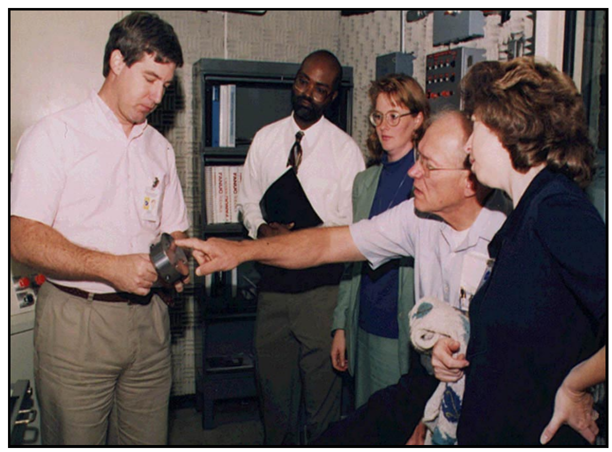

Figure 2.3-4. Hoppe (left) shows the Hammelmann rotary nozzle, used in the WaterJet stripping technique, to Clark, Broad, Wehe, and Driscoll.

Figure 2.3-5. Driscoll inspects a panel stripped with the WaterJet method. The patterns on the panel are produced as water from the nozzle blasts the topcoat and primer off the panel.

3.0 ACTIVITIES DURING SEQUENCE 3

3.1. Sample Preparation and Aging

Cleaning and coating activities were completed for 175 control panels, which were aged in four batches in preparation for depainting during Sequence 3. (See Table 3.1-1.)

Table 3.1-1. Aging Schedule

Batch	Aging Duration	Control Panels for Use in	Quantity
1	3/4/97 to 4/28/97	Chemical Stripping	50
		CO_2 Laser Stripping[1]	9
2	3/31/97 to 5/27/97	Plastic Media Blasting	29
		Sodium Bicarbonate Wet Stripping	9
3	4/28/97 to 6/23/97	WaterJet Blasting	24
4	5/27/97 to 7/2/97	FLASHJET® Coating Removal[2]	24
		ENVIROSTRIP® Wheat Starch Blasting	30

Notes: 1. One of the original 10 panels remains at the former vendor's facility.
2. One of the original 25 panels was used to assess the effects of overheating during processing.

3.2. Depainting Processes

This study is being conducted on chemical strippers that do not contain methylene chloride and on six mechanical stripping processes: FLASHJET® coating removal, CO_2 laser stripping, plastic media blasting, sodium bicarbonate wet stripping, WaterJet blasting, and ENVIROSTRIP® wheat starch blasting. All test fixtures include aluminum backing plates for the 0.016-inch substrates, which are extremely thin and flexible.

After Sequence 1, the TAC decided to eliminate two CO_2 blasting processes (TOMCO$_2$ and COLDJET™) from the study. After Sequence 2, the TAC pursued CO_2 laser stripping with a new vendor to optimize logistics. (See Section 3.2.4.)

The study's scope is limited to one coating system on two substrates to obtain results in a timely manner that could provide the most benefit to facilities that depaint aerospace hardware. A test protocol encompassing different paint systems or processing and operating parameters may yield different results.

3.2.1. Chemical Stripping

During the third depainting sequence, this process was used to strip 50 control panels cut from clad and non-clad 2024-T3 aluminum sheets (0.064 inch thick). Four alkaline/neutral products (Gage Stingray 874B and Turco 6813, 6813-E, and 6840-S) and four acid products (Turco 6776, McGean-Rohco Cee-Bee E-1004B, Calgon EZE 540, and Eldorado PR-2002) were tested alongside two methylene chloride strippers (McGean-Rohco alkaline Cee-Bee R-256 and acid Cee-Bee A-202), which acted as baselines. The aforementioned chemical strippers will be tested for the remainder of the study.

The chemical stripping investigators have adopted the basic procedure observed during a site visit to Raytheon (discussed in Section 2.1 of the *Fourth Progress Report*), which will be used for the remainder of the study. The strippers were initially applied in a thin mist, followed by a slightly heavier mist approximately 30 minutes later. The paint surface was checked approximately every 2 hours. If any paint showed release, the panel surface was lightly brushed using a brass bristle brush, and then the stripper was reapplied in the same manner. Temperatures were kept within a range of 75 to 82 °F, with an average relative humidity of 36%. (See Table 3.2.1-1.)

Table 3.2.1-1. Test Parameters for Chemical Stripping (Sequence 3)

Substrate Thickness (in.)	**Application Method**	**Depainting Facility Temperature** (°F)	**Average Relative Humidity**
0.064	Spray or brush on	75 to 82	36%

All chemical strippers removed 100% of the paint system from these control panels. (See Table 3.2.1-2.) Detailed results are discussed below and in Appendix A.2.1.

Table 3.2.1-2. Average Results for Chemical Stripping (Sequence 3)

Chemical Type	**Approximate Dwell Time** (hr)	**Post-Stripping Surface Roughness** (μin.)	**Coatings Removed**
Alkaline/Neutral	4	10.2	100% topcoat and 100% primer
Acid	3	10.1	

Note: These averages do not include any baseline data from the two methylene chloride strippers.

During Sequence 3, all chemical strippers had dwell times that were similar to those seen in a comparison with Sequence 2 data. (See Tables 3.2.1-3 and 3.2.1-4.)

Table 3.2.1-3. Average Test Data for Alkaline/Neutral Strippers (To Date)

Chemical Product	Average Dwell Time per Sequence			Average Surface Roughness (µin.)						
				Baseline	After Stripping			After Cleaning		
	Seq. 1	Seq. 2	Seq. 3	Measure-ment	Seq. 1	Seq. 2	Seq. 3	Seq. 1	Seq. 2	Seq. 3
Cee-Bee R-256[1]	30 min	7 min	5 min	1.2	1.9	11.2	10.9	12.5	11.7	11.6
Gage Stingray 874B[2]	–	7 hr	5 hr	1.5	–	6.6	10.6	–	7.2	8.8
Turco 6813	9 hr	3.5 hr	4 hr	2.1	2.7	10.6	9.6	11.1	10.1	10.5
Turco 6813-E	6 hr	5 hr	2.5 hr	2.7	2.8	9.5	9.4	9.6	9.1	9.5
Turco 6840-S	8 hr	4.5 hr	5 hr	2.2	2.2	11.1	11.8	10.8	12.4	12.2

Note:
1. Cee-Bee R-256 is a methylene chloride product being used as the alkaline/neutral baseline.
2. Gage Stingray 874B entered the study during Sequence 2; therefore Sequence 1 data do not exist for this product.

Table 3.2.1-4. Average Test Data for Acid Strippers (To Date)

Chemical Product	Average Dwell Time per Sequence			Average Surface Roughness (µin.)						
				Baseline	After Stripping			After Cleaning		
	Seq. 1	Seq. 2	Seq. 3	Measure-ment	Seq. 1	Seq. 2	Seq. 3	Seq. 1	Seq. 2	Seq. 3
Cee-Bee A-202	30 min	5 min	4 min	1.3	1.6	10.0	10.5	10.6	10.4	10.3
Cee-Bee E-1004B	6 hr	4 hr	3.5 hr	1.3	1.7	11.7	10.6	12.0	11.0	11.3
EZE 540	9 hr	5 hr	2.5 hr	1.2	1.5	9.9	10.4	11.0	10.3	10.3
PR-2002	9 hr	4 hr	3.5 hr	1.3	1.5	9.9	9.6	10.3	9.4	10.3
Turco 6776	6 hr	2.5 hr	2.5 hr	1.4	1.4	10.2	9.9	11.4	10.8	10.4

Note: Cee-Bee A-202 is a methylene chloride product being used as the acid baseline.

Dwell times ranged from 2.5 to 5 hours for the alkaline/neutral strippers, while the alkaline methylene chloride baseline stripped in 5 minutes. (See Table 3.2.1-5.) Dwell times ranged from 2.5 to 3.5 hours for the acid strippers, while the acid methylene chloride baseline stripped in 4 minutes. (See Table 3.2.1-6.)

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Plans had called for both Stingray 874 and 894 to be added as alkaline/neutral strippers during Sequence 2. Gage Products Company, however, requested that these plans be canceled in favor of adding only Stingray 874B (a modified version of the Stingray 874 formulation tested during our site visit to the Raytheon facility in May 1996), which they consider a more promising product. Stingray 874B did not show signs of brightening or alodine removal during Sequence 2, unlike the product tested at Raytheon (as described in the *Fourth Progress Report*, Section 2.1). Since these test specimens entered the study during Sequence 2, they were not subjected to the phosphoric acid bath used during Sequence 1 that produced significant etching, which increased surface roughness values for the other test specimens.

Figures 3.2.1-1 through 3.2.1-3 show the setups for the chemical stripping tests. Figures 3.2.1-4 through 3.2.1-8 show comparisons of the debonding stages produced by the various stripping agents.

The MSFC points of contact are EH33/Robin Broad at (256) 544-7016 and EH33/Regina Moore at (256) 544-8456.

Figure 3.2.1-1. Test Setup of Methylene Chloride Panels (initial to intermediate debonding)

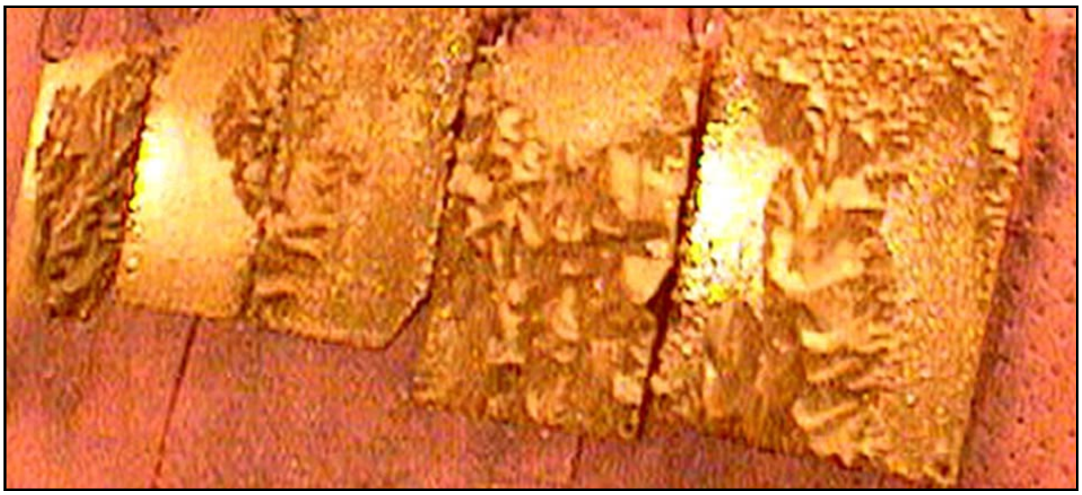


Figure 3.2.1-2. Test Setup of Alkaline/Neutral Panels (intermediate debonding)

Figure 3.2.1-3. Test Setup of Acid Panels (intermediate debonding)

Figure 3.2.1-4. Intermediate Debonding on 0.064-in. Panel Brushed with Methylene Chloride Stripper

Figure 3.2.1-5. Full Debonding on 0.064-in. Panel Brushed with Methylene Chloride Stripper

Figure 3.2.1-6. Initial Debonding on Panel Sprayed with Non-Methylene Chloride Stripper

Figure 3.2.1-7. Intermediate Debonding on Panel Sprayed with Non-Methylene Chloride Stripper

Figure 3.2.1-8. Full Debonding on Panel Sprayed with Non-Methylene Chloride Stripper

3.2.2. CO_2 Blasting

No further testing will be conducted on the CO_2 blasting process, which was shown to be ineffective as a stand-alone paint removal process during Sequence 1.

3.2.3. FLASHJET® Coating Removal

During the third depainting sequence, this process was used to strip 24 control panels cut from non-clad 2024-T3 aluminum sheets that were 0.016 inch thick (14 specimens), 0.051 inch thick (4 specimens), and 0.064 inch thick (6 specimens). In July 1997, these panels were shipped to McDonnell Douglas Aerospace (MDA) in St. Louis, Missouri. (MDA became Boeing-St. Louis in August 1997 and, beginning with this report, will be referred to by that name.) By December 1997, all were stripped and returned to MSFC. (See Table 3.2.3-1 for test parameters.)

Table 3.2.3-1. Test Parameters for FLASHJET® Coating Removal (Sequence 3)

Coating Layer	Input Voltage (V)	Repetition Rate (flashes/sec)	Stand-off Distance (in.)	Trans-lational Velocity (in./sec)	Stripping Passes	CO_2 Input Pressure to Nozzle (psi)	Media Flow Rate (lb/hr)	CO_2 Angle of Attack (deg)
Topcoat	1900 to 2300	3 to 5	2 to 3	0.75 to 1.4	8	90 to 180	500 to 1000	21 to 29
Primer					4			

Note: Boeing-St. Louis considers specific FLASHJET® parameters to be proprietary information.

After stripping, the panels were visually inspected at MSFC. Table 3.2.3-2 shows average results, while Appendix A.2.3 gives detailed results.

Table 3.2.3-2. Average Results for FLASHJET® Coating Removal (Sequence 3)

Substrate			Time to Strip[1] (min:sec)	Strip Rate (in.^{2}/min)	Surface Roughness After Stripping[2] (μin.)	Coatings Removed[3]
Dimensions (in.)	**Thickness** (in.)	**Area Stripped** (in.^{2})				
22 by 22	0.016	484	6:55	70.0	20.5	–
	0.051	484	3:40	132.0	18.2	–
	0.064	484	4:48	100.8	17.2	–
12 by 12	0.064	144	1:34	91.9	16.6	–

Notes: 1. **Time to Strip** includes time used to make overlapping passes, which did not increase the amount of coating removed.

2. **Surface Roughness After Stripping** was measured even though coating remained on the substrate. This remaining coating was measured for its thickness and is reported in Tables 3.2.3-3 through 3.2.3-5. Figure 3.2.3-1 shows the location of measurements taken on the panels.

3. **Coatings Removed** are percentages based on pre-strip thickness data presented in Appendix 2.3 (primer: 0.6 to 0.9 mil; topcoat: 1.7 to 2.3 mil) and post-strip thickness data presented in Tables 3.2.3-3 through 3.2.3-5. Percentages of primer removed are shown in Table 3.2.3-6; virtually all topcoat was removed.

Table 3.2.3-3. Post-Strip Coating Thickness Readings for 0.016-in. Panels

Panel Number	**Substrate Thickness** (mil)	**Average Post-Strip Coating Thickness** (mil)	**Maximum Post-Strip Coating Thickness** (mil)	**Minimum Post-Strip Coating Thickness** (mil)	**Standard Deviation** (mil)
IV-14.1	16	0.26	0.32	0.11	0.07
IV-14.2	16	0.27	0.33	0.22	0.04
IV-14.3	16	0.31	0.41	0.15	0.09
IV-15.5	16	0.33	0.39	0.28	0.04
IV-15.6	16	0.32	0.39	0.21	0.06
IV-15.-7	16	0.37	0.46	0.24	0.07
IV-15.8	16	0.32	0.42	0.22	0.07
IV-15.9	16	0.34	0.48	0.20	0.08
IV-15.10	16	0.37	0.65	0.25	0.12
IV-15.11	16	0.35	0.46	0.24	0.08
IV-15.12	16	0.34	0.41	0.24	0.06
IV-16.13	16	0.34	0.40	0.28	0.04
IV-16.14	16	0.27	0.34	0.23	0.03
IV-16.15	16	0.30	0.35	0.21	0.05

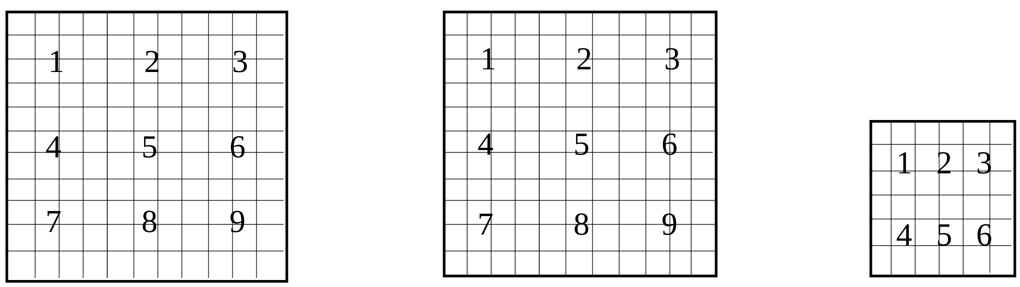
Table 3.2.3-4. Post-Strip Coating Thickness Readings for 0.051-in. Panels

Panel Number	**Substrate Thickness** (mil)	**Average Post-Strip Coating Thickness** (mil)	**Maximum Post-Strip Coating Thickness** (mil)	**Minimum Post-Strip Coating Thickness** (mil)	**Standard Deviation** (mil)
IV-9.5	51	0.19	0.23	0.17	0.02
IV-9.1	51	0.17	0.22	0.12	0.04
IV-9.2	51	0.20	0.25	0.16	0.03
IV-9.3	51	0.23	0.30	0.19	0.04

Table 3.2.3-5. Post-Strip Coating Thickness Readings for 0.064-in. Panels

Panel Number	Substrate Thickness (mil)	Average Post-Strip Coating Thickness (mil)	Maximum Post-Strip Coating Thickness (mil)	Minimum Post-Strip Coating Thickness (mil)	Standard Deviation (mil)
IV-I-1.10.2	64	0.32	0.36	0.27	0.03
IV-I-1.10.3	64	0.33	0.39	0.28	0.04
IV-I-1.9.2	64	0.32	0.35	0.30	0.02
IV-I-1.9.3	64	0.32	0.34	0.30	0.01
IV-I-1.9.4	64	0.30	0.33	0.27	0.02
IV-9.3	64	See Note.	See Note.	See Note.	See Note.

Note: Data were not recorded.



0.016-in. panels (22 in. by 22 in.)

0.051-in. panels (22 in. by 22 in.)

0.064-in. panels (12 in. by 12 in.)

Figure 3.2.3-1. Paint Thickness Reading Locations

During Sequence 2, as reported in the *Fifth Progress Report*, localized heating occurred in 11 of 15 of the 0.016-inch panels because only their outer edges were restrained by the test fixture. This method was inadequate to prevent a 22- by 22-inch sheet of thin-gauge material from being lifted toward the flashlamp by the vacuum system. For Sequence 3, Boeing-St. Louis designed, built, and used a vacuum hold-down fixture, which prevented lifting of the panels during stripping (Figure 3.2.3-2). The reader should note that such difficulties probably will not occur in actual service, where fabricated structures are unlikely to include an unsupported span of this length and gauge.

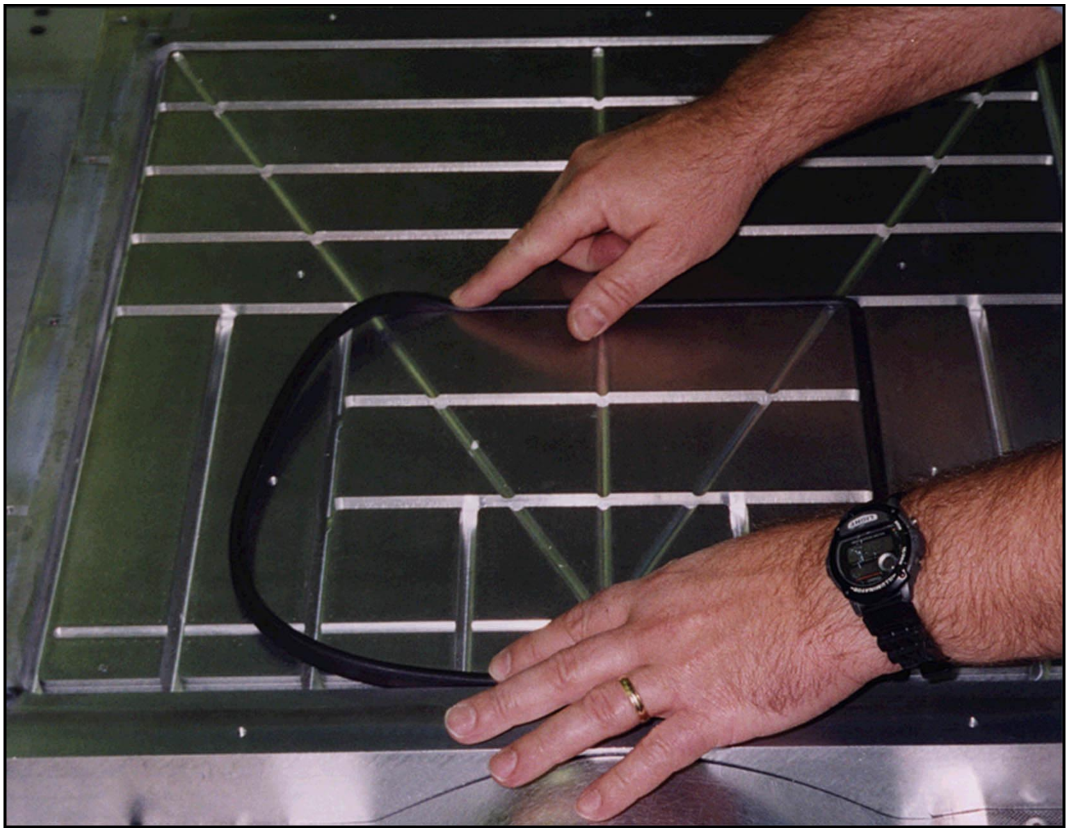


Figure 3.2.3-2. Boeing-St. Louis designed a vacuum plate to provide support to both the 22-in. by 22-in. panels and the 12-in. by 12-in. panels during FLASHJET® stripping. A technician installs a rubber gasket seal into the vacuum plate groove for 12-in. by 12-in. panel stripping.

After stripping, some control panels again contained residual primer that was not uniform over each panel's surface. Boeing-St. Louis' preferred approach is to leave approximately 0.5 mil or less of primer. Table 3.2.3-6 shows the approximate percentages of primer removed from the panels.

Table 3.2.3-6. Percentage Primer Removed

Panel Thickness (mil)	**Average Primer Thickness** (mil)	**Thickness Remaining** (mil)	**Percent Remaining** (%)	**Percent Removed** (%)
0.016	0.75	0.32	43	57
0.051	0.75	0.19	26	74
0.064	0.75	0.32	42	58

Note: Average Primer Thickness: (0.6 + 0.9)/2 = 0.75 mil

The non-uniform residual coating may be related to two factors: uneven paint thickness and uneven stripping, which occurs because the lamp's intensity is higher in the center of each stripping width and tapers off on each end. The FLASHJET® system can compensate somewhat by slightly overlapping each stripping pass and varying pass directions.

The MSFC point of contact is EH33/Steve Burlingame at (256) 544-8860.

3.2.4. CO_2 Laser Stripping

Panels to be CO_2 laser stripped during the third depainting sequence have been delivered to new TAC committee member, General Lasertronics Corporation of Santa Clara, California. Sequence 3 data for CO_2 laser stripping will be presented in the final report.

The MSFC point of contact is EH33/Steve Burlingame (256) 544-8860.

3.2.5. Plastic Media Blasting

During the third depainting sequence, this process was used to strip 29 control panels cut from non-clad 2024-T3 aluminum sheets that were 0.016 inch thick (12 specimens), 0.051 inch thick (3 specimens), and 0.064 inch thick (14 specimens). This process was also used to strip 10 control panels cut from clad 2024-T3 aluminum sheets that were 0.016 inch thick (5 specimens) and 0.032 inch thick (5 specimens). (See Table 3.2.5-1.)

Table 3.2.5-1. Test Parameters for Plastic Media Blasting (Sequence 3)

Substrate Thickness (in.)	**Pressure** (psi)	**Angle of Attack** (deg)	**Stand-off Distance** (in.)	**Media Flow Rate** (lb/hr)	**Mesh Size**
0.016	30	30	8 to 12	250 to 500	16/20 and 20/30 mix (20/80%)
0.032	35	30 to 45			
0.051	35	30			
0.064	40	30 to 45			

Note: Low pressures were used to blast these substrates to avoid bending caused by induced residual stresses. Early in the study, it became apparent that the 0.016-in. control panels could not be blasted at pressures higher than 30 psi without bending.

Testing was conducted at MSFC using a PMB unit from Titan Abrasive Systems (Model 6060SDCR). Type V plastic media were deployed, using a nozzle with an inside diameter of 0.5 inches at the throat. Strip rates were improved slightly by increasing the flow rate of the plastic media, as well as by combining some 16/20 mesh media with smaller 20/30 mesh media (at a ratio of 20 to 80%, respectively) to increase the aggressiveness of this process. Media effectiveness was noticeably reduced after ~10 strip sequences. Table 3.2.5-2 shows average results for the non-clad samples; Tables 3.2.5-3, 3.2.5-4, and 3.2.5-5 show average results for the clad samples; and Appendix A.2.5 gives detailed results.

Table 3.2.5-2. Average Results for Plastic Media Blasting of Non-Clad Samples (Sequence 3)

Substrate Thickness (in.)	Stripped Area ($in.^2$)	Time to Strip (min:sec)	Strip Rate ($in.^2/min$)	Surface Roughness After Stripping (μin.)	Coatings Removed
0.016	484	17:50	27.08	20.9	100% topcoat and 80% primer
0.051	484	14:52	32.50	28.6	
0.064	144	5:21	26.99	14.2	

Table 3.2.5-3. Average Results for Plastic Media Blasting of Clad Samples (Sequence 1)

Substrate Thickness (in.)	Stripped Area ($in.^2$)	Time to Strip (min:sec)	Strip Rate ($in.^2/min$)	Surface Roughness After Stripping (μin.)	Coatings Removed
0.016	484	23:09	20.9	37.5	100% topcoat and 80% primer
0.032	484	22:15	21.8	120.8	

Table 3.2.5-4. Average Results for Plastic Media Blasting of Clad Samples (Sequence 2)

Substrate Thickness (in.)	Stripped Area ($in.^2$)	Time to Strip (min:sec)	Strip Rate ($in.^2/min$)	Surface Roughness After Stripping (μin.)	Coatings Removed
0.016	484	21:13	22.8	40.2	100% topcoat and 80% primer
0.032	484	19.10	25.3	94.0	

Table 3.2.5-5. Average Results for Plastic Media Blasting of Clad Samples (Sequence 3)

Substrate Thickness (in.)	Stripped Area ($in.^2$)	Time to Strip (min:sec)	Strip Rate ($in.^2/min$)	Surface Roughness After Stripping (μin.)	Coatings Removed
0.016	484	17:31	27.63	See Note	100% topcoat and 80% primer
0.032	484	16:07	30.06	See Note	

Note: Because of an anomaly during processing, these data are not available.

Beginning in Sequence 3, our laboratory procedures were modified to adopt process parameters that are more representative of production stripping in the field. For Sequences 1 and 2, we used a nozzle with an inside diameter of 0.25 inches at the throat. For Sequences 3 and 4, we are using a nozzle with an inside diameter of 0.5 inches at the throat. (This change increased the stripping rate.) The 3-inch stand-off distance was increased to 8 to 12 inches during this cycle.

The MSFC point of contact is EH33/Johnnie Clark at (256) 544-2799.

3.2.6. Sodium Bicarbonate Wet Stripping

Data for the third depainting cycle for this process will be reported in the final report.

The MSFC point of contact is EH33/David Hoppe at (256) 544-8836.

3.2.7. WaterJet Blasting

Data for the third depainting cycle for this process will be reported in the final report.

The MSFC point of contact is EH33/David Hoppe at (256) 544-8836.

3.2.8. ENVIROSTRIP® Wheat Starch Blasting

During the third depainting sequence, this process was used to strip 30 control panels cut from non-clad 2024-T3 aluminum sheets that were 0.016 inch thick (19 specimens), 0.051 inch thick (5 specimens), and 0.064 inch thick (6 specimens). In late July 1997, they were shipped to the ENVIROSTRIP® Test Center (jointly operated by ADM/Ogilvie and CAE Electronics, Ltd.) in Montreal, Quebec, Canada. By early September 1997, all panels had been stripped and returned to MSFC.

The panels were depainted using ENVIROSTRIP® wheat starch media in a typical production mix, determined by removing various coating systems at standard operating parameters (20 to 40 psi, 8 to 18 lb). New media (12 to 30) were continuously added to the mix at a rate of 10 to 15% per cycle. The mix had a broad particle size range (12 to 120), the majority being between 20 and 100.

During Sequence 3, the manual system produced strip rates similar to those reported for Sequence 2 for the 0.051-inch and 0.64-inch thick panels; the manual strip rates for the six 0.016-inch thick panels fell between those of the first and second sequences (data appearing in the *Fifth Progress Report*). The semi-automatic system also produced strip rates similar to those reported for Sequence 2.

The MSFC point of contact is EH33/Steve Burlingame at (256) 544-8860.

3.2.8.1. Manual

Manual blasting was performed on 11 control panels cut from non-clad 2024-T3 aluminum sheets that were 0.016 inch thick (6 specimens), 0.051 inch thick (2 specimens), and 0.064 inch thick (3 specimens). (See Table 3.2.8.1-1.)

Table 3.2.8.1-1. Test Parameters for Manual ENVIROSTRIP® Wheat Starch Blasting (Sequence 3)

Substrate Thickness (in.)	Pressure (psi)	Media Flow Rate (lb/min)	Mesh Size	Projection Angle (deg)	Stand-off Distance (in.)	Stripping Width (in.)
0.016	20	18	12 to 120	30 to 60	4 to 8	0.75
0.051	30	12				
0.064	30	12				

The operator used a standard 0.5-inch double venturi nozzle. No statistically significant changes were seen in surface roughness values, which remained well within acceptable levels. Table 3.2.8.1-2 shows average results, while Appendix A.2.8 gives detailed results.

Table 3.2.8.1-2. Average Results for Manual ENVIROSTRIP® Wheat Starch Blasting (Sequence 3)

Substrate Thickness (in.)	Time to Strip (min:sec)	Strip Rate ($in.^2$/min)	Surface Roughness After Stripping (µin.)	Coatings Removed
0.016	3:03	71.0	18.7	100% topcoat and 99% primer
0.051	2:04	105.3	17.0	
0.064	1:58	110.0	15.2	

3.2.8.2. Semi-Automatic

Semi-automatic blasting was performed on 19 panels cut from non-clad 2024-T3 aluminum sheets that were 0.016 inch thick (13 specimens), 0.051 inch thick (3 specimens), and 0.064 inch thick (3 specimens). (See Table 3.2.8.2-1.)

Table 3.2.8.2-1. Test Parameters for Semi-Automatic ENVIROSTRIP® Wheat Starch Blasting (Sequence 3)

Substrate Thickness (in.)	Translational Velocity (in./sec)	Pressure (psi)	Media Flow Rate (lb/min)	Mesh Size	Projection Angle (deg)	Stand-off Distance (in.)	Stripping Width (in.)
0.016	1.2	20	18	12 to 120	45	3	4.25
0.051	2.1	40	12				
0.064	2.1	40	12				

The test system included a computer-controlled four-axis gantry-style robotic system designed by CAE, with a CAE T-7 flat nozzle**.** No statistically significant changes were seen in surface roughness values, which remained well within acceptable levels. Table 3.2.8.2-2 shows average results, while Appendix A.2.8 gives detailed results.

Table 3.2.8.2-2. Average Results for Semi-Automatic ENVIROSTRIP® Wheat Starch Blasting (Sequence 3)

Substrate Thickness (in.)	Time to Strip	Strip Rate (in.^{2}/min)	Surface Roughness After Stripping (μin.)	Coatings Removed
0.016	44	293.3	19.9	100% topcoat and 99% primer
0.051	24.2	535.5	15.1	
0.064	24.2	535.5	15.7	

3.3. Surface Roughness

These measurements allow determination of any changes to the roughness of the substrate surface that may have been caused by the depainting processes under study. SAE MA4872 (draft 4) requires that all surface roughness measurements remain <125 microinches after a minimum of 5 depainting cycles. Surface roughness measurements that exceed this requirement may indicate that the substrate's structural integrity has been compromised.

The test specimens were measured using a Giddings and Lewis profilometer and a Hommelwerke T500 profilometer (operator choice). Both give values of R_a, the arithmetic mean roughness value, and both were checked with the same roughness standard before taking measurements.

Surface roughness measurements were taken at a number of locations on each substrate, the number varying according to test specimen size. The original baseline measurements were made after the test specimens were cut, cleaned, and iridited (but before they were coated and aged for the first stripping sequence). During each sequence, each test specimen was measured after stripping and after cleaning in preparation for coating and aging during the next sequence. (See Tables 3.3-1, 3.3-2, and 3.3-3.)

The most significant effect in surface roughness to date has been a one-time attempt to use a phosphoric acid bath to remove alodine and residual coatings from the control panels after stripping during Sequence 1. As a result, surface roughness values unexpectedly increased during post-cleaning measurements for Sequence 1, which led to a decision to remove the phosphoric acid bath from the cleaning procedure. (See Section 3.1.1, *Fifth Progress Report*.)

Post-stripping surface roughness values for Sequences 2 and 3 for the chemical stripping, FLASHJET®, and ENVIROSTRIP® wheat starch processes showed little change from post-cleaning surface roughness values for Sequence 1. For the plastic media blasting process, the surface roughness measurements for all panels increased dramatically from the baseline to the first post-stripping measurements. The first post-stripping surface roughness measurements for two of these panels surpassed the 125-microinch limit, but as they were cleaned, their surface roughness dropped below this limit. The Sequence 1 post-cleaning surface roughness measurements for all the PMB clad panels decreased. With further processing during Sequence 2, the surface roughness measurements continued to decrease. Possible reasons for this include (1) the decrease in remnant primer after stripping as our stripping skills improved, (2) the fact that it is not possible to take each set of measurements at precisely the same points on a substrate, and (3) the possibility that, during each depainting cycle, some clad material may be lost, so that the measurements would have been made on the smoother, bare material**.**

The MSFC point of contact is EH12/Miria Finckenor at (256) 544-9244.